

NUMERICAL ANALYSIS OF THE RESPONSE OF PILE-RAFT SYSTEMS CONSIDERING THE APPLICATION OF CEMENT AND POLYPROPYLENE FIBER TREATMENT

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Received: 20.02.2018; Revised: 12.04.2019; Accepted: 22.05.2019

Abstract

Long-term performance of civil engineering projects mainly depends on the strength of underground layers. When the underground soil layers are problematic or have low bearing capacity and strength against the applied loads, application of soil stabilization methods can be effective. In this study, performance of pile-raft systems using stabilized/reinforced soil under foundation is investigated. For validation, the obtained numerical results were compared with the existing results from analytical and numerical analyses. Using the experimental data available in the literature, the variations of stiffness and strength parameters were simulated by three-dimensional finite element method and then foundation response was evaluated for each case. According to the obtained results, depending on the pile-raft configuration, different strategies of stabilization with cement, reinforcement with polypropylene fibers, or a combination of cement stabilization and fiber reinforcement can be employed to reduce the differential and maximum settlements of foundation and to improve the overall performance. In general, even though reinforcement with fibers has a positive influence on the tensile and shear strength of soil, the effect of cement stabilization on the design parameters of the foundation is more pronounced. Finally, an implementation of cost analysis of stabilization project was proposed to be conducted based on the applied materials and improvement/cost ratio.

Keywords: Cement stabilization; Pile-raft system; Polypropylene fiber; Settlement; Three-dimensional finite element method.

1. INTRODUCTION

By growing population and lack of appropriate soils, many civil engineering projects have to be constructed on weak soils, which have a great potential of failure due to low strength and high compressibility of underlying soil. Therefore, various improvement methods such as physical stabilization [1, 2], chemical stabilization [3–6], reinforcement with fibers [7, 8] and geotextile [9, 10] are utilized. Polypropylene fibers are cheap and strong against different environmental conditions and also can be pre-opened easily. These fibers have high modulus of elasticity and poor bond strength. Although this deficiency may be addressed by any sort of pre-treatment techniques, providing high volumes of uniform (parallel distribution) mixtures from them is not convenient due to development of weak planes.

For this reason, randomly distributed fibers are used for soil reinforcement. Randomly distributed fibers limit potential planes of weakness that can develop parallel to oriented reinforcement. Fiber-reinforced soil has appropriate shear and tensile strengths that can be applied for construction of retaining walls and protection of slopes. In recent years, many investigations have been conducted on the enhancement of soil performance using polypropylene fibers. Maher and Gray [11] performed laboratory triaxial compression tests to determine the static stress-strain response of sands reinforced with discrete randomly distributed fibers and found that randomly distributed fiber inclusions significantly increase the ultimate strength and stiffness of sands. Puppala and Musenda [12] investigated the effectiveness of fiber reinforcement on

strength, swell and shrinkage characteristics of expansive clays. Miller and Rifai [13] focused on the impact of fiber reinforcement on workability, compaction characteristics, hydraulic conductivity and development of desiccation cracks in compacted clay samples. Consoli et al. [14] studied the behavior of polypropylene-fiber-reinforced sand under large shear strains and showed the great potential of polypropylene fiber for soil reinforcement because the increase of soil strength did not deteriorate even at very large strains. Hejazi et al. [15] reviewed the history, advantages, applications and possible executive problems of using different types of natural and synthetic fibers in soil reinforcement. Li and Zornberg [16] carried out triaxial compression and fiber pullout tests to assess how the fiber tension is mobilized for varying shear strain levels.

In addition, fibers can be added to cement or lime stabilized soils to prevent their brittle failure. Kaniraj and Havanagi [17] studied the individual and combined effects of randomly oriented fiber inclusions and cement stabilization on the geotechnical characteristics of fly ash-soil mixtures and showed that depending on the type of fly ash-soil mixture and curing period, the increase in strength caused by the

combined action of cement and fibers is either more than or nearly equal to the sum of the increase caused by them individually. Tang et al. [18] performed an experimental program to investigate the effects of discrete short polypropylene fibers on the strength and mechanical behavior of cemented clayey soil. The test results indicated that the inclusion of fiber reinforcement within cemented soil caused an increase in the unconfined compressive and shear strengths and changed the brittle behavior of cemented soil to a more ductile one. Khattak and AlRashidi [19] studied the laboratory durability and mechanistic evaluation of soil-cement mixtures reinforced with processed cellulose and polypropylene fibers and reported that the fiber reinforcement can resist the tensile or shrinkage crack formation in the soil-cement mixtures for road bases and improve the structural capacity and performance of pavements significantly. Consoli et al. [20] investigated stress-dilatancy behavior of cemented sand reinforced with randomly discrete polypropylene fibers and found that fiber reinforcement increases peak strength just up to a certain cement content and decreases stiffness. Chen et al. [21] reinforced cement-stabilized soft Shanghai clay using fiber bundles split from waste polymer textile bags and depicted

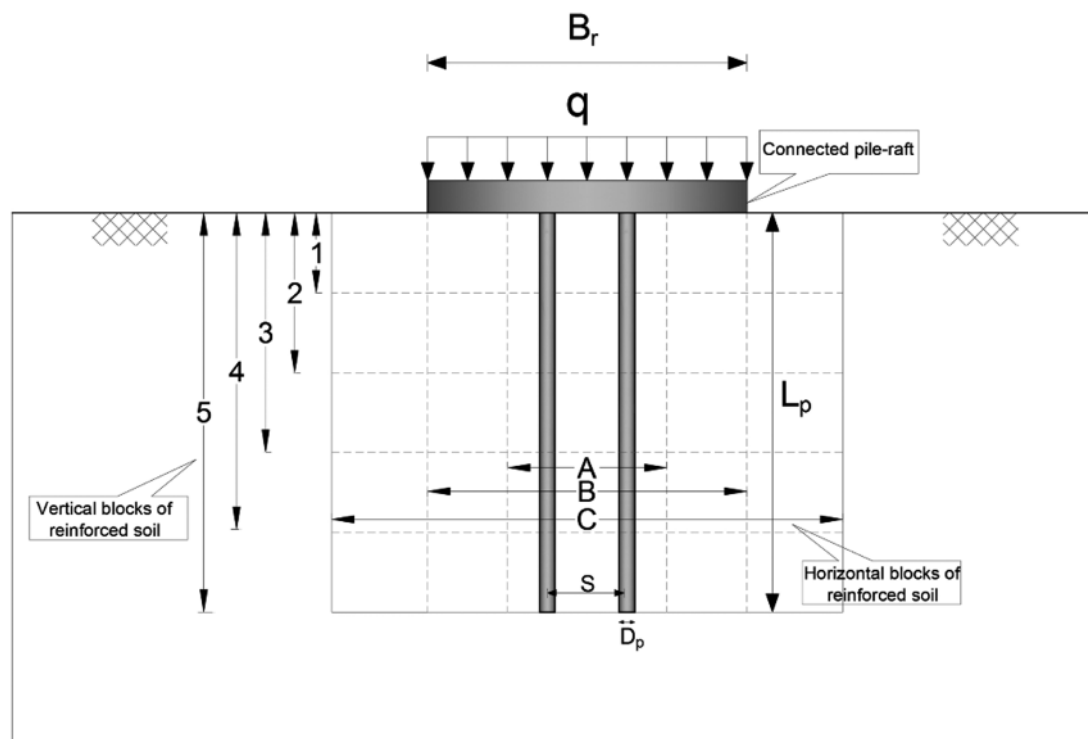


Figure 1.
Stabilized soil blocks division

Table 1.
Material properties of Nanjing soil [18]

Soil properties	Values
USCS Classification	CL
Specific gravity	2.7
Liquid limit	36.4%
Plasticity index	17.8%
Optimum moisture content	16.5%
Maximum dry density	1.7 g/cm ³
D ₆₀	0.0117 mm
D ₃₀	0.0048 mm
D ₁₀	0.0011 mm

Table 2.
Index and strength parameters of PP-fiber [18]

Behavior parameters	Values
Fiber type	Single fiber
Unit weight	0.91 g/cm ³
Average diameter	0.034 mm
Average length	12 mm
Breaking tensile strength	350 MPa
Modulus of elasticity	3500 MPa
Fusion point	165°C
Burning point	590°C
Acid and alkali resistance	Very good
Dispersibility	Excellent

ed that these fibers can considerably enhance the strength and ductility of the cemented clay. Recently, Hazirbaba [22] carried out a series of direct shear and CBR tests to evaluate the mechanical behavior of geofibre-reinforced sand in non-submerged and submerged conditions. Using statistical analyses, Festugato et al. [23] presented a relationship for determination of an appropriate amount of fibers for improvement of tensile and compressive strengths of cemented soil. Divya et al. [24] investigated the hydraulic conductivity of soil reinforced with PP-T fiber and PET fiber of various lengths. The factors influencing the tensile strength of fiber reinforced fine grained soils under freeze-thaw condition were evaluated by Li et al. [25].

Most of the performed investigations about fiber-reinforced cemented soils focused on their strength properties and stress-strain behavior but there are limited studies conducted on the improvement of the behavior of a foundation constructed on these types of soils. In this paper, using results of experimental tests, the effect of fiber reinforced cement-stabilized (FRCS) soil on the performance of pile-raft systems is studied. For this purpose, 3D finite element

numerical method was used and load-settlement behavior of foundations with/without cement and fibers was evaluated.

2. STABILIZED SOIL BLOCKS

As observed in Fig. (1), in order to study the effect of width and depth of stabilized soil on the performance of foundation, soil under foundation was divided into vertical and horizontal blocks. This division has been axisymmetric in such a way that the letters show the block width and the numbers indicate the block depth. The blocks A, B and C are of width of 5, 10 and 15 m, respectively, with height increment of 1m. For instance, the block of B3 in Fig. (1) shows stabilized soil with the width of 10 and depth of 3 m.

3. MATERIALS

In order to model soil behavior, experimental results obtained by Tang et al. [18] for the soil of Nanjing area, China were applied. Table (1) presents physical and mechanical properties of soil. Ordinary Portland cement with compressive strength (28-day) of 33.4 MPa and specific surface of 387 m²/kg was used for stabilization of this soil. Properties and strength parameters of polypropylene (PP) fibers used for soil reinforcement are listed in Table (2). For each amount of cement and fiber, soil modulus of elasticity and strength parameters such as cohesion and internal friction angle were adapted from Tang et al. [18]. Table (3) presents 12 cases of reinforcement and stabilization considered in this study. As described by Tang et al. [18], the values of cohesion and internal friction angle of soil were determined from direct shear testing of soil. The values of elastic modulus of each soil mixture were also estimated from the correlation between the unconfined compressive strength of soil (reported by Tang et al. [18]) and elastic modulus proposed in the literature. The nomination of each case is based upon the sample number mentioned in this table, as FRCS1 corresponds to the soil no. 1.

Table 3.
Material properties of different cases considered in this study [18]

Sample no.	Cement content (%)	Fiber content (%)	Modulus of elasticity E (MPa)	Poisson's ratio	Unit weight (kN/m ³)	Cohesion c (kPa)	Angle of internal friction ϕ (degrees)
1	0	0	5.8	0.2	16.7	75.1	27.3
2	0	0.05	5.6	0.2	16.7	95.3	28.2
3	0	0.15	5.5	0.2	16.7	102.5	30.1
4	0	0.25	5.3	0.2	16.7	114.3	31.6
5	5	0	39.5	0.3	16.7	152.1	34.2
6	8	0	50.7	0.3	16.7	171.8	35.3
7	5	0.05	39.2	0.3	16.7	169.4	35.1
8	5	0.15	38.8	0.3	16.7	186.7	36.3
9	5	0.25	38.5	0.3	16.7	193.4	36.7
10	8	0.05	50.4	0.3	16.7	181.4	37.0
11	8	0.15	49.9	0.3	16.7	193.3	37.5
12	8	0.25	49.3	0.3	16.7	229.8	39.3

4. NUMERICAL MODELING

To investigate the behavior of the pile-raft system, numerical analyses were performed using 3D finite element analysis.

4.1. FE model

The soil and foundation structure were discretized into 8-node linear brick elements. Fig. (2) shows a typical finite element mesh used for analysis. All the staged modeling and finite element analyses were conducted using geotechnical software package PLAXIS 3D Foundation. In order to reduce the computational effort, only one-quarter of the problem was modelled due to load and geometry symmetry. The degrees of freedom on lateral planes were blocked of moving in a perpendicular direction to these surfaces and the base of the model was constrained against translation in three directions. Based on the previous studies, the depth of the model was assumed to be more than twice the pile length [26, 27] and the lateral boundaries were considered to be more than the raft breadth [28]. The in-situ condition was simulated by producing the geostatic stresses in the first stage of loading. Then, a uniform load was applied over the raft area. Based on the long-term response of the soil, drained effective parameters of the soil were used.

In this study, to simulate the soil constitutive behavior, Mohr-Coulomb model was utilized. In all analyses, average (constant) values of material properties were used for each layer of the reinforced or stabilized soil. Owing to having a great modulus of elas-

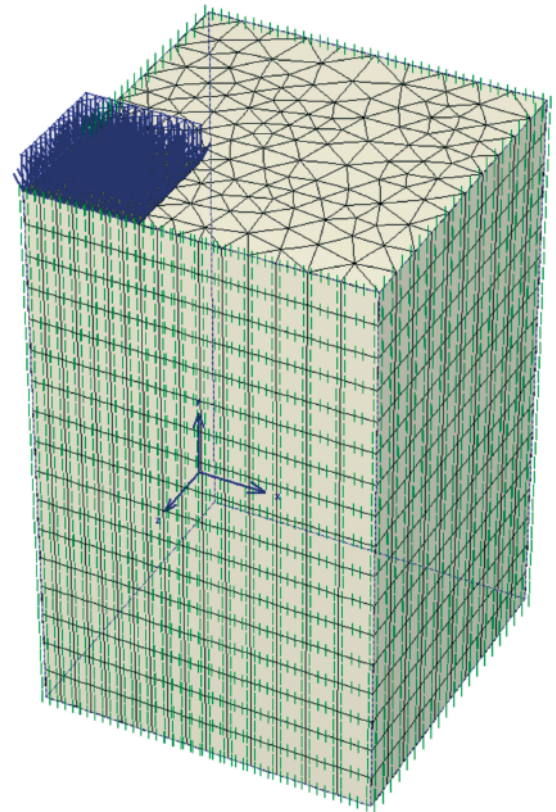


Figure 2.
Typical 3D FE mesh of the one-quarter model

ticity in comparison with the soil, the structural elements of pile-raft were modelled with a linear elastic model. The connection between the raft beneath and pile head was assumed to be rigid. At the pile-soil

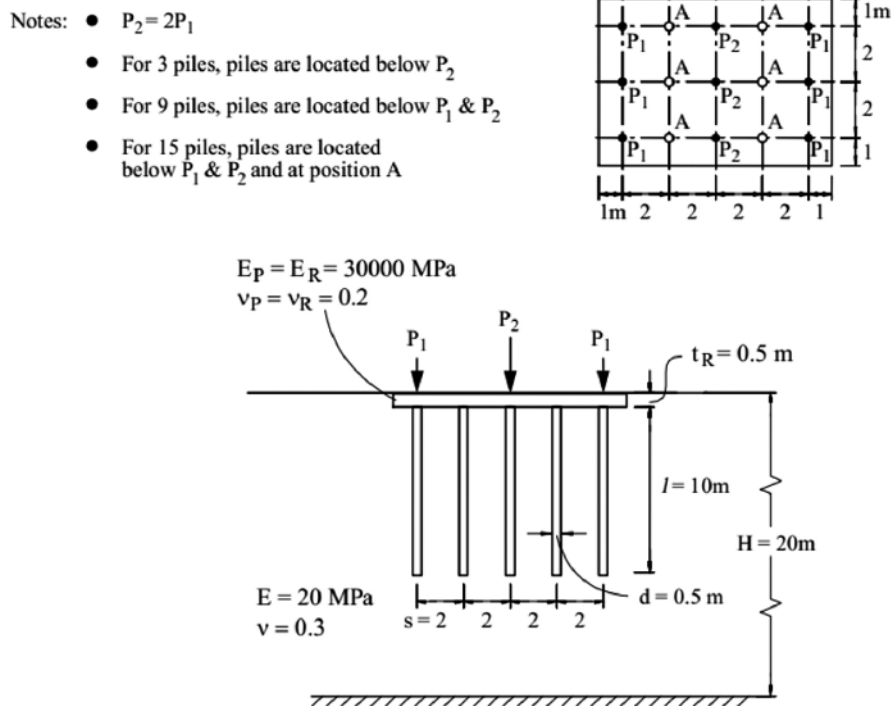


Figure 3. Soil, pile-raft material properties and load configuration for validation [30]

interface, thin-layer interface with the properties of soil material and the thickness of $0.1D_P$ (D_P = pile diameter) was used [29].

In addition to modeling boundary condition, applied vertical load and the geometry of different cases based on the dimensions of reinforcement blocks, material properties of concrete foundation, reinforced and/or stabilized soil and surrounding soil needs to be used as input parameters. It should be mentioned that while the material properties of foundation and soil are constant for different cases, the inclusion of different percentages of fibers and cement will change the input parameters such as elastic modulus, Poisson's ratio, cohesion, and internal friction angle (see Table 3).

4.2. Validation

To verify the FE model used to perform the analysis of pile-raft system on the stabilized soil, a simple problem of a $10 \times 6 \times 0.5$ m raft supported by a pile group containing 15 piles was simulated, including a 3×5 arrangement of piles where hollow circles show unloaded piles and solid black circles depict loaded piles (center piles are loaded by $P_2 = 2P_1$, edge piles are loaded by P_1). Pile, raft, soil properties and the

load characteristics are shown in Fig. (3).

The methods considered to compare the results with the present method are finite difference method employing FLAC2D and FLAC3D programs [30], plate on spring approximation method [31] using GARP5, simplified PDR method and strip on spring method using GASP [32]. The obtained load-settlement curves were depicted in Fig. (4) to compare the results.

As indicated in Fig. (4), for low load levels, approximation and simplified methods are also in good agreement with the numerical methods (3D FDM and FEM). Although the results are slightly different for higher load levels, the consistency of the general load-settlement behavior is agreeable. However, FLAC2D overestimates the settlements because of the assumptions involved in plane strain modeling.

The validation of the FE model was also conducted through a comparison with the centrifuge test of a small pile-raft system by Horikoshi and Randolph [33]. They tested a model of circular raft with a prototype thickness of 50 mm and diameter of 14 m supported by a 3×3 array of 15 m long piles with the diameter of 0.32 m spaced at 2.5 m. A vertical load of 12 MN was applied uniformly over the whole raft area. Table (4) shows a summary of the comparison

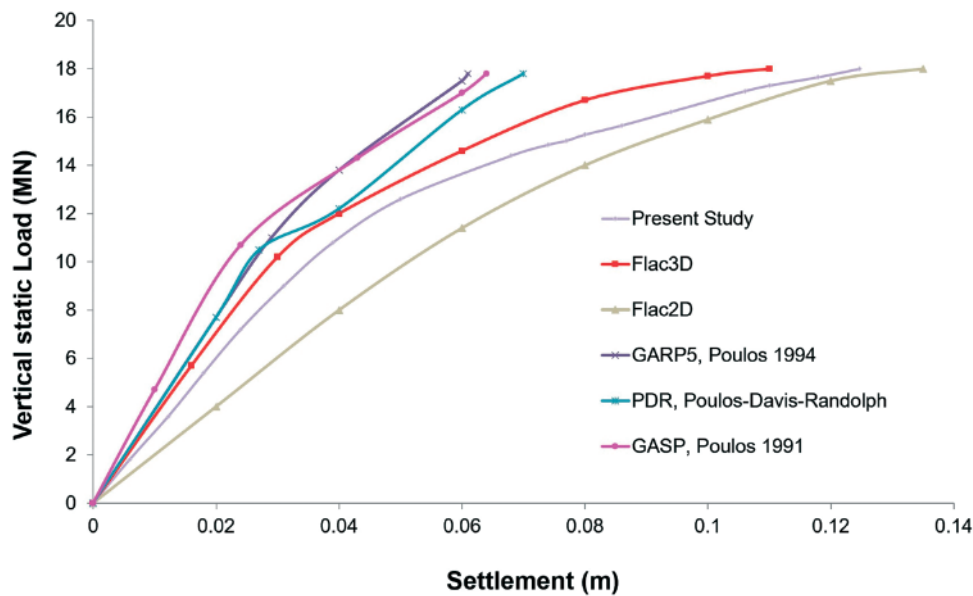


Figure 4.
Comparison of the load-settlement curves from different analysis methods

Table 4.
Comparison of the settlement from centrifuge test [33] and present study

Model	Average settlement (mm)	Load taken by piles (%)
Horikoshi and Randolph [33]	22	19
Present study	21	20

of the settlements and pile loads of pile-raft from centrifuge test and present study. This good agreement of the results indicates the validity of the present FE model to predict the response of pile-raft.

5. RESULTS AND DISCUSSIONS

As mentioned before, in this study, individual and combined effects of fiber-reinforced and cement-stabilized soil on the response of pile-raft system are investigated. The effects of cement stabilization and fiber reinforcement on maximum bending moment at the center of the raft foundation, maximum settlement (typically occurring at the center of raft foundation) and differential settlement between the corner and center of the raft foundation are evaluated. Moreover, the effects of stabilized blocks dimensions, number and spacing of piles on foundation behavior are assessed. In all of the cases, raft dimensions are $10 \times 10 \times 1$ m and load is 80 kPa. For the base model that is mostly used, the number, length, diameter and spacing of piles are 4, 5 m, 1 m and 4 m,

respectively. In other cases, the changes to each parameter are mentioned accordingly.

5.1. The effect of block width

Generally, maximum settlement in pile-raft systems occurs at the center of raft and occasionally, application of piles is for reduction of this maximum settlement. Therefore, maximum settlement is considered as one of the important parameters for evaluation of foundation performance. Fig. (5) indicates variation of maximum settlement of pile-raft with stabilized blocks having widths of A, B and C, according to Fig. (1).

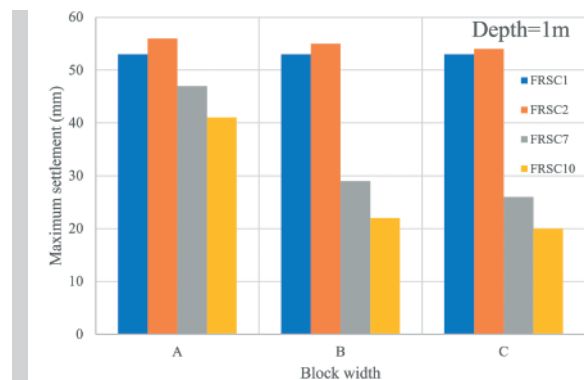


Figure 5.
The variation of maximum settlement of pile-raft with the width of reinforced block

For this purpose, the settlement behavior of a pile-raft system (4 piles having length of 5m and spaced at 4m) was studied in cases FRCS1 (unreinforced soil), FRCS2 (with 0.05% fibers), FRCS5 (unreinforced soil with 5% cement), FRCS6 (unreinforced soil with 8% cement), FRCS7 (with 5% cement and 0.05% fibers) and FRCS10 (with 8% cement and 0.05% fibers) up to 1m depth of fiber reinforcement and/or cement stabilization (the term stabilized depth is used hereafter to describe the depth of reinforcement and/or stabilization). As observed in Fig. (5), variation of block width does not affect maximum settlement of fiber-reinforced (unstabilized) soil significantly. However, by comparing FRCS2, FRCS7 and FRCS10, it is obvious that block stabilization with 5% cement can decrease foundation maximum settlement by up to 40%. However, for cases considered in this section, the variation of settlement would not exceed 20% by increasing the cement content from 5% to 8% by the weight of the soil. In addition, by comparison of FRCS1 and FRCS2, it is observed that adding 0.05% fiber does not improve foundation performance considerably.

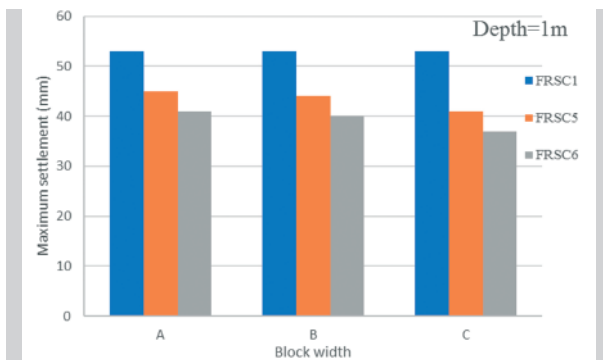


Figure 6.
The variation of maximum settlement of pile-raft with the width of stabilized block

As observed in Fig. (6), adding 5% cement to the soil block can decrease the maximum foundation settlement by approximately 18% while the effect of expanding the stabilized block width on reducing the maximum foundation settlement is less than 5%. It indicates the lower influence of the properties of soil at the periphery of the foundation compared to the soil beneath the center of the foundation.

5.2. The effect of block depth

Fig. (7) demonstrates variation of foundation maximum settlement with block depth for two different

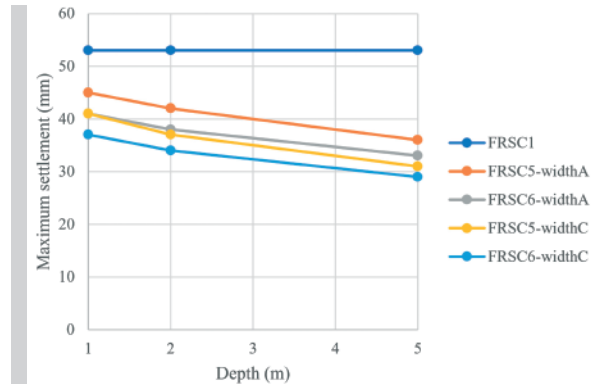


Figure 7.
The variation of maximum settlement of pile-raft with the depth of reinforced block

widths. The pile-raft with no reinforcement or stabilization has been considered as a base case having high settlements. As observed in Fig. (7), foundation maximum settlement decreases about 8 to 15% with increasing stabilized block depth from 1 to 5 m. By comparison of orange and gray curves, it can be found that reinforcement width can be decreased with increasing cement content.

5.3. The effect of pile group properties

In this section, the effect of pile group properties (such as number and spacing of piles) on the pile-raft foundation behavior is studied. Since differential settlement of the foundation, as a function of the underlying soil stiffness, has a notable effect on the resulting bending moment in the raft and thus is an important factor in the analysis and design of pile-raft systems [34], it was studied in this section as a parameter influencing the foundation behavior.

5.3.1. The effect of pile spacing

Fig. (8) indicates the effect of pile spacing of 4 and 6 m on the foundation differential settlement. Considering the pile diameter of $D_p=1$ m, the pile spacing ratio of $S/D_p=4$ and 6 are consistent with suggested pile spacing in Validation section ($S/D_p=4$ in van Impe [30]) and other previous studies such as Taghavi Ghalesari and Janalizadeh Choobbasti [29] and Prakoso and Kulhawy [35]. The differential settlement is an important parameter for design of pile-raft foundation because it affects bending moment. The increase of pile spacing reduces differential settlement insignificantly except for FRCS2 case in which 0.05% fiber was used for soil reinforcement. This reduction of differential settlement was expect-

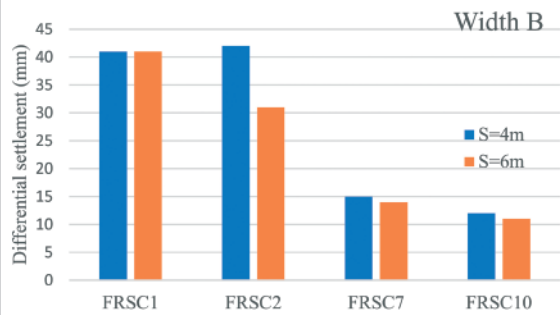


Figure 8.
The effect of pile spacing on the differential settlement (between the corner and center of raft) of pile-raft system

ed due to distribution of load between the piles at wider range; however, when the effect of fiber reinforcement (and not stabilization) is prominent (FRCS2), a better performance in frictional (tensile) load transfer would contribute to the better load distribution and lower differential settlement. Generally, adding cement for constant amounts of fiber and pile spacing decreases differential settlement by about one-third.

5.3.2. The effect of pile numbers

In structural design of foundations, bending moments caused by loads are very important. Hence, appropriate evaluation of these moments is necessary. Fig. (9) indicates the effect of using 4 and 9 piles on bending moment. The hollow circle shows a piled raft foundation having 4 piles without any stabilization or reinforcement. As observed, for unstabilized/unreinforced foundation, bending moment decreases about 18% with increasing number of piles.

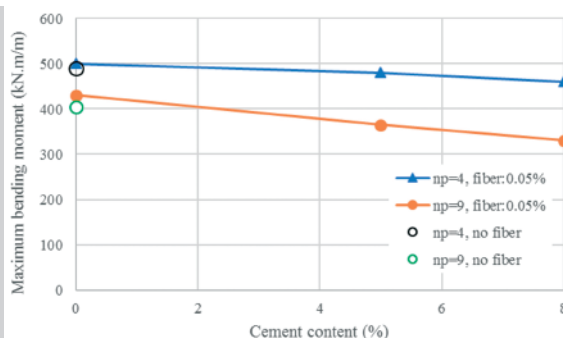


Figure 9.
The effect of the number of piles on the maximum bending moment of the foundation for various amounts of cement content

With fiber reinforcement and stabilization of soil with 5 and 8% cement, the bending moments for a certain number of piles (e.g., 4 piles) does not alter considerably. Therefore, the effect of increasing pile number and spacing on the improvement of the behavior of pile-raft foundation constructed on stabilized soil is not as considerable as the conventional pile-raft.

5.3.3. Individual and combined effects of pile length and dimensions of stabilized blocks

In this section, a pile-raft with 4 piles of the diameter of 1 m and varying lengths located at the 4 m spacing is considered. Fig. (10) shows the effect of pile length and dimensions of stabilized blocks on the maximum bending moment of foundation.

By comparing the first three columns of the figure, it can be found out that in unstabilized soil, increasing the pile length more than two times (from 5 to 12.5 m) leads to a decrease of bending moment at the center of raft surface by about 20%. FRCS6 shows stabilization of soil with 8% cement and A4, C4, A5 and C5 indicate stabilized block dimensions. Therefore, it can be found that for pile length of 5 m, increase of block dimensions reduces bending moment at the center of raft surface. The bending moment of foundation decreases to one-third in comparison with unreinforced one with increasing block dimensions to A4 and pile length to 10 m. It can be concluded that increase of block dimensions and pile length can improve foundation performance. Hence, it is not necessary to increase both of them for reduction of settlement and bending moment because it will not be economic.

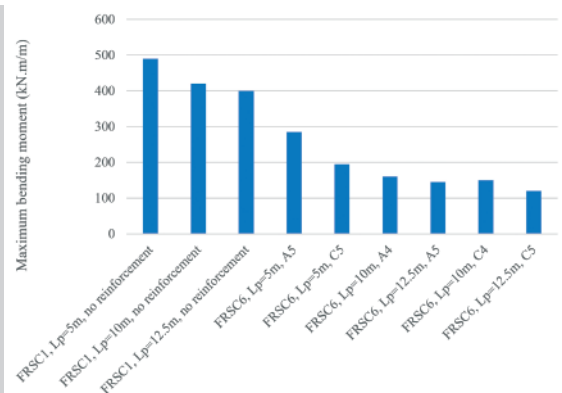


Figure 10.
The influence of pile length and reinforced soil block dimensions on the resulting maximum bending moment at the center of raft surface

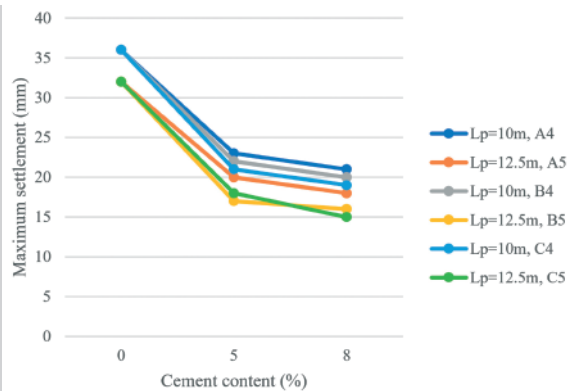


Figure 11.
The variation of pile-raft maximum settlement with cement content for various pile lengths and block sizes

5.4. The effect of cement

Fig. (11) indicates variation of maximum settlement of pile-raft foundation with cement content. Some cement-stabilized (without any reinforcement) cases for piles with lengths of 10 and 12.5 m having spacing of 4m were considered. Stabilized block depths were considered in accordance with pile lengths. As observed, the maximum settlement of pile-raft decreases significantly with increasing cement content from 0 to 5% so that this reduction will reach to 50%. The effect of stabilization with 8% cement on the decrease of maximum settlement of pile-raft is less than stabilization with 5% cement specially for longer piles so that the maximum settlement reduces only about 15% in this case. This trend was expected because as mentioned in most studies in the literature, there is a certain limit for the percentage of cement application for soil stabilization (typically less than 10%) beyond which adding cement would have no or negative impact on the foundation response. Furthermore, the rate of improvement with increasing block width from A to C or block depth from 4 to 5 is not significant. If it is necessary to select an optimized case, an economic analysis can be carried out.

5.5. The effect of fibers

Fig. (12) shows variation of maximum and differential settlements of pile-raft foundation with fibers. For this purpose, FRCS1-4 for pile-raft with 4 piles having length of 5m and spacing of 4m were considered. As expected, soil stiffness decreases and strength parameters (c and ϕ) increase with increasing polypropylene fibers. In addition, the maximum settlement of pile-raft slightly increases due to the

increased rate of consolidation, which can be ignored due to the advantageous properties of fibers in improving tensile strength of soil. The differential settlement of pile-raft increases about 10 to 17% depending on the dimensions of reinforced blocks. The differential settlement of foundation for A1 block is more than B3 and C5 blocks.

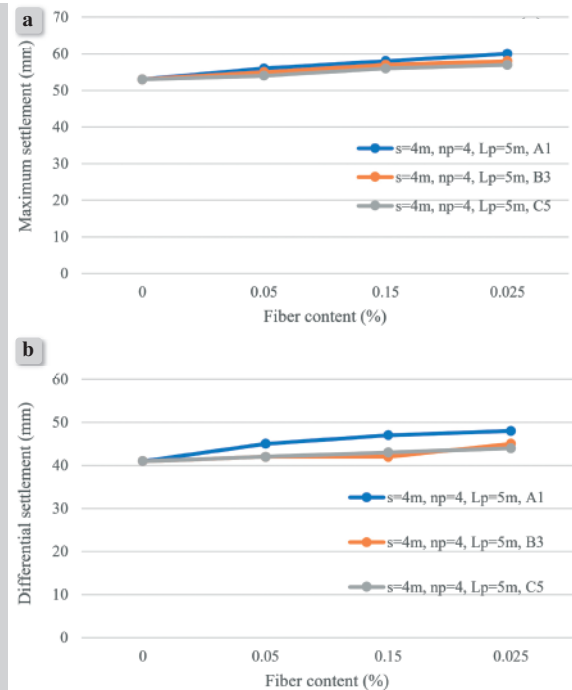
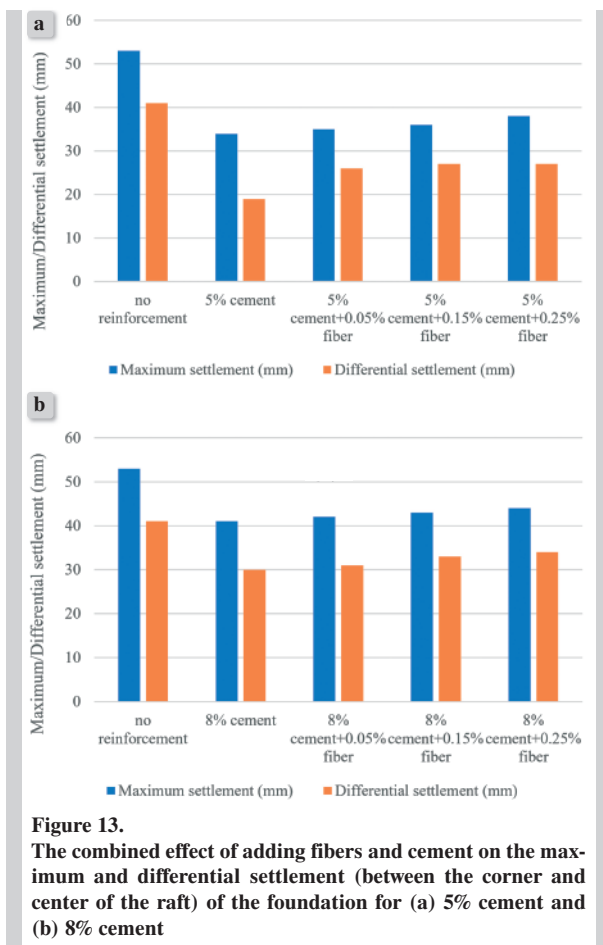


Figure 12.
The relationship between the (a) maximum (b) differential settlement (between the corner and center of the raft) of pile-raft and fiber content

5.6. The combined effect of cement and fibers

In previous sections, the effect of cement stabilization or fiber reinforcement on settlement and bending moment of pile-raft foundation was studied. In this section, the combined effect of cement and fibers on behavior of pile-raft foundation is investigated. For this purpose, FRCS7-12 cases were considered. As presented in Table (3), FRCS7 to 9 and FRCS10 to 12 depict stabilization with 5% and 8% cement for different percentages of fibers, respectively. Fig. (13) shows combined effect of adding fibers and cement on the maximum and differential settlement of pile-raft foundation. In order to compare with unstabilized or only cement-stabilized cases, FRCS1, FRCS5 and FRCS6 were also considered. As observed in

Fig. (13), maximum and differential settlements decrease substantially with increasing cement content. According to economic considerations, B3 and A1 blocks were considered for stabilization with 5% and 8% cement, respectively. Although settlements decreased with increasing cement content (Fig. 11), the foundation behavior has been improved using B3 rather than A1 due to its larger depth and width. It should be noted that in each of the studied cases, adding fiber to cement does not change settlements significantly. Therefore, for cement-stabilized fiber-reinforced cases, cement is more effective than fiber in decreasing foundation settlement. The important point in design of pile-raft foundations is economic analysis and evaluation of reinforcement or stabilization effect on performance of these foundations.



6. CONCLUSIONS

In this study, the data collected from experimental test were used to conduct a series of 3D finite element analyses of pile-raft systems on the soil blocks treated by fiber reinforcement and cement stabilization. The individual and combined effect of reinforcement and stabilization of underlying soil with various amounts of stabilizers as well as the effect of pile-raft system characteristics were investigated. According to the results, even though the addition of PP fibers to the soil might improve the tensile strength of the soil, it has no significant effect on the maximum and differential settlement of the foundation and bending moment in the raft, which are important factors in the design. On the other hand, by adding 5% cement to the mixture, these parameters can be improved to an acceptable level. A summary of the obtained results can be listed as:

1. The width of the reinforced/stabilized soil block has a more prominent effect (up to 40% decrease) on the maximum settlement of the foundation where the soil block is stabilized with cement. Although fiber reinforcement enhances the tensile strength of soil block, fiber reinforcement without stabilization of soil has no considerable influence on the maximum settlement.
2. An increase of the depth of reinforced/stabilized soil block by 5 times can only change the reduction of the maximum settlement of the pile-raft from 8 to 15%. It shows that the increase of the width of the stabilized soil block is a more effective solution in decreasing the foundation settlements compared to the increase of the depth of the stabilized soil block.
3. The effect of pile spacing on the differential settlement (and subsequently maximum bending moment) of pile-raft system is more considerable when the fiber reinforcement (and not stabilization) is utilized for the soil block below the foundation. Maximum bending moment of pile-raft on unstabilized/unreinforced soil block has higher reduction (about 18%) with increasing the number of piles from 4 to 9 piles in comparison with pile-raft on stabilized soil block.
4. In practice, a comparison between the individual effect of cement stabilization or fiber reinforcement as well as the combined effect of stabilization and reinforcement on each design factor (e.g., maximum settlement, differential settlement, maximum bending moment) should be taken into consideration. As an example, in the present study, sta-

bilization of larger soil block (B3) with lower cement content (5%) and fiber content (0.05%) indicated better performance in terms of maximum/differential settlement as compared to the case with smaller soil block (A1) with higher cement stabilization (8%) and fiber reinforcement (0.25%).

Therefore, it was found that a design alternative considering pile-raft configuration (specially pile length), size of reinforcement block and certain amount of stabilizer can be chosen to obtain an optimum design to be implemented in economic analysis.

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